

Instabilities and the Formation of Small-Scale Structures in Planetary Nebulae

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Abstract. Recent observations have revealed the presence of a variety of small-scale “micro-structures” in Planetary Nebulae images. I discuss numerical hydrodynamics models of planetaries and outline the formation and growth of instabilities that may be seen in these models. It is possible that these may be the forerunners of some of the observed small-scale structures.

1. Introduction

It has become clear in recent years that the morphology of Planetary Nebulae (PNe) is much more complicated than was previously thought. This revolution has been brought about mainly due to spectacular observations of PNe using the Hubble Space Telescope (see reviews by Bruce Balick, Howard Bond, Raghendra Sahai and others in this volume), accompanied by images of proto-planetary and young planetary nebulae, especially in infrared bands. The variety of structure visible at small scales, from rings, arcs, and disks to FLIERS, Jets and Ansaе, is well described elsewhere in this volume.

The global morphology of PNe has generally been attributed to the so-called interacting stellar winds model (Kwok, Purton and Fitzgerald 1978), where a “fast” stellar wind from a post-AGB star interacts with a structured ambient medium, presumably a wind ejected at an earlier epoch. However the variety of filaments, blobs, fast-moving knots and “searchlight beams” seen in the HST observations are not easily explained.

High-resolution numerical simulations of planetary nebulae reveal the presence of instabilities that arise during the nebular evolution. These instabilities are due to various flow patterns, which in turn depend on the initial conditions and the hydrodynamic model assumed. It is possible that they may give rise to some of the small-scale structure visible in PNe images. In this paper we study the formation and growth of some of these instabilities. More details can be found in Dwarkadas & Balick (1998a, hereafter DB98).

2. Various Types of Models

Numerical models of Planetary Nebulae can be considered as falling into these basic categories:

(a) **Constant Wind Models** - Models where the wind properties are constant throughout the evolution of the nebula. (b) **Evolving Wind Models** - The wind properties change with time during the course of evolution of the nebula. (c) **Magnetohydrodynamic (MHD) Models** - Magnetic field responsible for the asymmetry. (d) **Radiation-Hydrodynamic (RHD) Models** - Incorporating a more realistic treatment of the radiation transfer.

In this paper I will discuss predominantly models in the first two categories. MHD models have been very comprehensively reviewed by Guillermo Garcia-Segura (this volume), and RHD models by Adam Frank and Garrelt Mellema (Frank 1999 and references therein).

2.1. Constant Wind Models

This is the prototypical PN model, where the very fast ($\approx 1000 \text{ km s}^{-1}$), low density wind collides with the slow ($\approx 10 \text{ km s}^{-1}$), dense wind from a previous epoch. Since the wind properties are constant, the nebula will reach a self similar stage in several doubling times of the radius, wherein it begins to expand with a constant velocity and the shape remains time-invariant (see for example Dwarkadas, Chevalier & Blondin 1996, hereafter DCB96). The constant expansion velocity does not allow for the growth of Rayleigh-Taylor instabilities.

If an asymmetry exists in the slow ambient wind, with denser material at the equator compared to the poles, the outcome will be an aspherical planetary nebula. A pressure gradient is created in the shocked fast wind due to this asymmetry, with higher pressure at the equator than the poles. This directs a flow along the walls from the equator to the poles (Figure 1). In addition, there is a tangential flow in the opposite direction within the dense shell (DCB96). The resultant shear flow leads to the growth of Kelvin-Helmholtz (K-H) instabilities along the edges, giving the edges a rippled appearance, as is seen in many PNe. The shell appears clumpy, but usually remains contiguous throughout the simulations. The corrugated appearance is primarily due to the asymmetry, and spherically symmetric PNe will not in general be susceptible to this instability.

2.2. Evolving Wind Models

Both stellar evolution models and observations of PNe seem to indicate an evolution in the wind properties over time. Despite significant progress in these areas (see articles by Schonberner and Wood) we still do not possess a good theoretical prescription for the characteristics of the mass loss, telling us how the wind properties change with time, and the relevant timescales.

Here I focus on results of simulations which were performed assuming that the wind velocity increases as a power law with time. The wind mass loss rate decreases correspondingly, such that the mass flux (or momentum flux) remains constant. The resultant instabilities do not depend strongly on the manner in which the wind properties vary, and we concentrate more on the general conditions that lead to the growth of the instability and in what stage of a PN's development they are likely to arise.

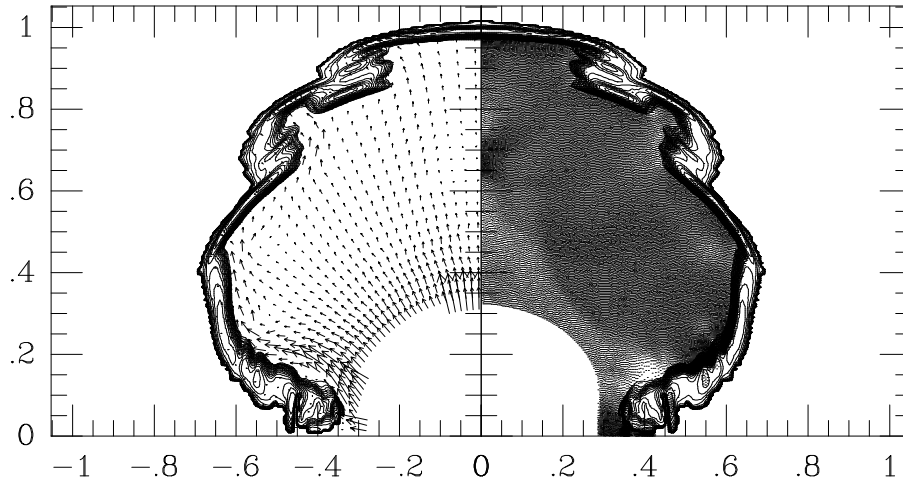


Figure 1. Density (RHS) and Velocity Vectors (LHS) from a simulation of an asymmetrical planetary using a constant-wind model.

If the velocity and mass loss rate of the so-called “fast wind” are slowly increasing, the nebula will go through an initial momentum-conserving or radiative stage. A radiative inner shock means there is no formation of a hot bubble, and the inner and outer shocks lie very close to each other (DB98), enclosing a thin shell of swept up material. A shear flow along the inner walls of the asymmetrical nebula gives rise to K-H instabilities. If the shell is thin these instabilities may grow to a size comparable to the shell thickness. In such a scenario the perturbations may continue to grow, giving rise to the non-linear thin shell instability (NTSI, Figure 2a). This arises when a thin shell, bounded between two sharp discontinuities, is perturbed by an amount larger than the thickness of the shell (Vishniac 1994). The perturbations tend to grow non-linearly, forming conical projections that are characterised by shear flow within the unstable fragments (Blondin & Marks 1998).

As the fast wind velocity increases and mass loss rate decreases, the time taken to radiate away the post-shock energy begins to exceed the flow rate. The inner shock ceases to be radiative, and a hot bubble of shocked fast wind separates it from the shocked ambient gas. As long as the velocity continues to increase, the high-pressure, low density bubble accelerates the low-pressure, high density swept-up material. The opposing density and pressure gradients lead to the growth of the Rayleigh-Taylor (R-T) instability, and wispy filaments can be seen growing inwards from the edges of the nebula (Figure 2b). These filaments, with bulbous shaped heads caused by the K-H instability as gas within the nebula flows around them, will continue to form as long as the wind velocity is evolving. Simultaneously, there still persists the shear flow along the inner wall of the nebula. This flow results in some of the filamentary material being constantly stripped off and mixed into the interior, leading to cold, dense and

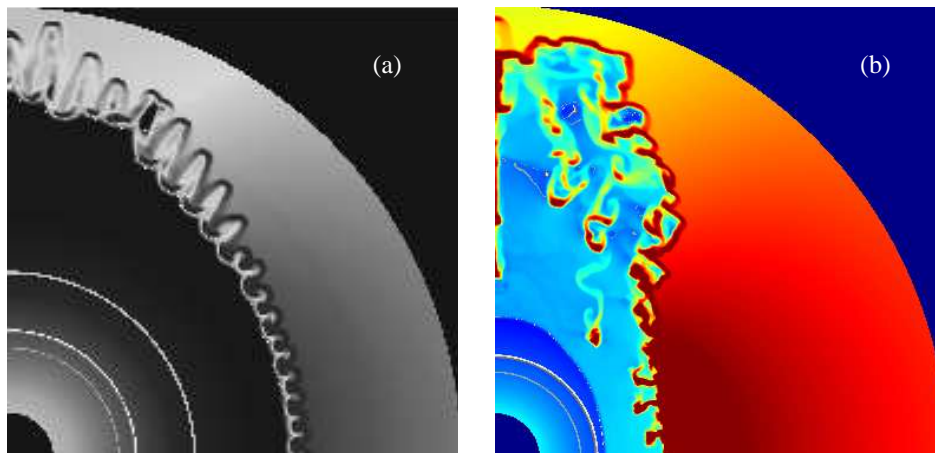


Figure 2. (a) The non-linear thin shell instability (b) The R-T instability.

slow moving material being mixed in with the high-temperature gas. The resultant flow within the hot bubble is characterised by the formation of vortices and the onset of turbulence.

Herein I have given a flavour for some of the instabilities that may occur. The filamentary appearance of many nebulae, such as Hubble 5 and NGC 6537, may be due to the R-T instabilities. R-T instabilities may also occur at ionization fronts (O'Dell & Burkert 1997). Many models of asymmetrical planetary nebulae require the presence of a dense torus of material surrounding the central star. The interaction of the stellar wind with this torus may lead to the formation of thin shell instabilities (see Dwarkadas & Balick 1998b). Other instabilities may be seen in RHD and MHD simulations. The next step will be to produce simulated images from the numerical simulations to enable a proper comparison with the observations.

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